EEC 4230 - Mobile Communication Systems

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Lecture 5: Mobile radio propagation: Large-scale path loss-II

Outline

Empirical Outdoor and Indoor Propagation Models

Empirical Propagation Models

- Log-normal Shadowing model gives more accurate PL estimation than the Log-distance model as it accounts for the variations in the received power over different times for the same Transmitter-receiver (T-R) separation.
- However, such variation will be different for different terrain, like Deserts, Forests, etc. This effect is not captured by Log-normal shadowing model.
- Several outdoor propagation models have been developed that account for specific terrain types. These are known as Empirical Models as they are empirical formulas derived from measurements.
- We will cover the most popular ones such as: (1) Okumura model (2) Hata model (3) COST-Hata model (4) recently, SUI model (Stanford University Interim model) for IEEE 802.16 (used in 4G,Wimax & LTE, cellular planning).

(1) Okumura Model (**Developed by Okumura in Tokyo**)

- Using extensive measurements, Okumura developed a set of curves giving the median (50%) attenuation relative to free space, in an urban area over a quasi-smooth terrain.
- Curves is developed using vertical omni-directional antennas at both BS (htx=200m) and MS (hrx=3m), and are plotted vs frequency and as a function of distance from the BS in the range 1km-100km (typical cell radius is 1.3km).
- It is useful for BS antenna heights of 30-1000m.
- The model can be used to predict signal attenuations for frequencies in the range 150 MHz to 1920 MHz, but it is typically extrapolated up to 3000 MHz (covers 2G/3G bands).
- This model is simple and accurate but no analytical explanation).
- To calculate the Okumura PL: (1) calculate free space PL (2) estimate extra attenuation for urban area from curves (3) add it to free space loss along with correction factors to account for terrain types & antenna heights.

Okumura, et al, "Field Strength and Its Variability in VHF and UHF Land Mobile Service," Riview Elect. Comm. Lab., 1968.

(1) Okumura Model

The model can be expressed as:

$$PL_{50}[dB] = L_F(f,d)[dB] + A_{mu}(f,d) - G_{h_{te}} - G_{h_{re}} - G_{AREA}$$

$$G_{h_{te}} = 20\log_{10}(\frac{h_{te}}{200}), \qquad 30m < h_{te} < 1000m$$

$$G_{h_{re}} = \begin{cases} 10\log_{10}(\frac{h_{re}}{3}), & \text{if } h_{re} \leq 3m \\ 20\log_{10}(\frac{h_{re}}{3}), & \text{if } 3m < h_{re} < 10m \end{cases}$$

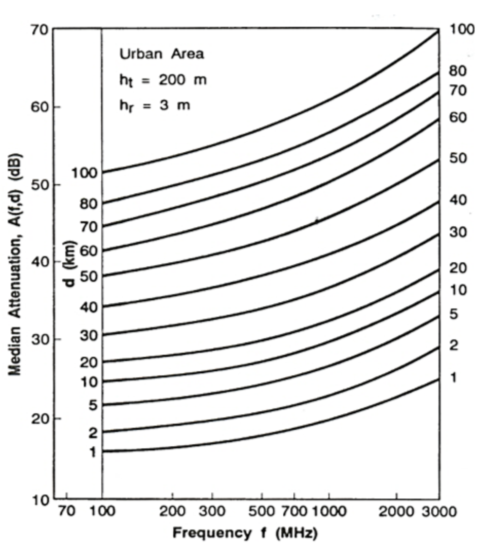
$PL_{50} = 50\%$ (median) value of propagation path loss

L_F = Free space propagation loss

A_{mu}= median attenuation relative to free space

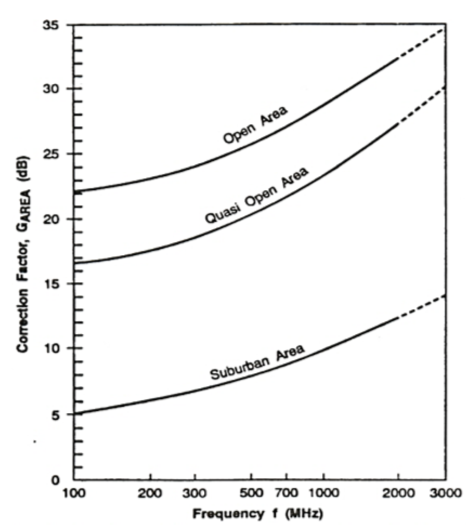
G_X = gain factor due to X

(1) Okumura Model



Upto 700-900MHz - modest attenuations,

Cellular service above 1GHz - severe attenuations



Correction factor G_{AREA} for different terrain types

Example 1:

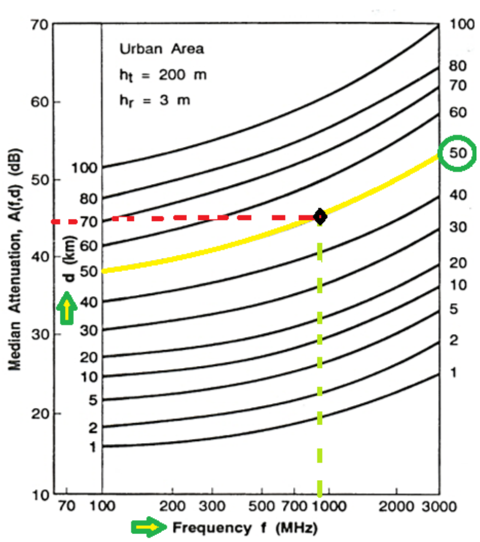
Find the median path loss using the Okumura's model for $d = 50$ km, $h_{te} = 100$ m, $h_{re} = 10$ m in a suburban environment. If the base station transmitter radiates an EIRP of 1 kW at a carrier frequency of 900 MHz, find the power at the receiver (assume a unity gain receiving antenna).

Solution

- $L_F = -10\log_{10}(\frac{\lambda}{4\pi d})^2 = 125.5$ dB, with $\lambda = c/f = \frac{3\times10^8}{900\times10^6} = \frac{1}{3}$.
- From the Okumura curves/Equations:
  $A_{mu}(900 \text{ MHz}, 50 \text{ km}) = 43$ dB, $G_{AREA} = 9$ dB,
- $G(h_{te}) = -6$ dB, $G(h_{re}) = 10.46$ dB,
- Thus $PL_{50}[\text{ dBm}] = 155.04$ dB.
- Therefore, the median received power is:

$$P_r(d)[\text{ dBm}] = EIRP[\text{ dBm}] - PL_{50}[\text{ dB}] + G_r[\text{ dB}]$$
$$= 60 \text{ dBm} - 155.04 + 0 = -95.04 \text{ dBm}$$

(1) Okumura Model



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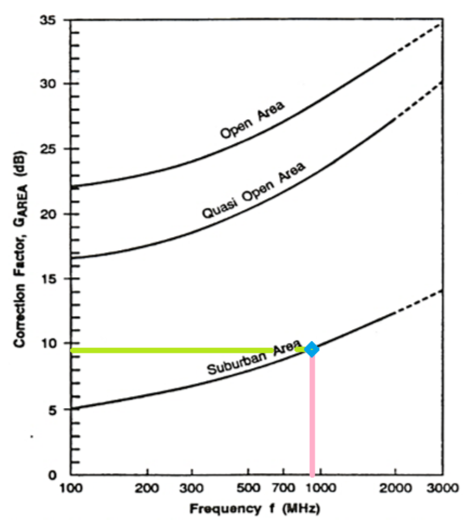


Correction factor G_{AREA} for different terrain types

(2) Hata Model

- Hata model is an empirical formulation of the graphical PL data provided by Okumura (to avoid reading error). Hata presented urban area as a standard formula and supplied correction equations to other situations. The standard formula for median PL **in urban areas**:

$$PL_{50}(urban)[dB] = 69.55 + 26.16\log_{10} f_c - 13.82\log_{10} h_{te} - a(h_{re}) + (44.9 - 6.55\log_{10} h_{te})\log_{10} d$$

  fc in MHz between 150MHz-1500MHz, h_{te} between 30m-200m, h_{re} between 1m-10m, d between 1-20 km, $a(h_{re})$ correction factor for MS antenna height.
- **For small & medium size city,**
  $a(h_{re}) = (1.1\log_{10} f_c - 0.7)h_{re} - (1.56\log_{10} f_c - 0.8)$ dB
- **For a large city,**
  $a(h_{re}) = 8.29(\log_{10} 1.54h_{re})^2 - 1.1$ dB $\quad f_c \leq 300$ MHz
  $a(h_{re}) = 3.2(\log_{10} 11.754h_{re})^2 - 4.97$ dB $\quad f_c > 300$ MHz
- To obtain PL in **suburban & rural areas**, standard Hata formula is modified:
  $PL_{50}(suburban) = PL_{50}(urban) - 2(\log_{10}(f_c/28))^2 - 5.4$
  $PL_{50}(rural) = PL_{50}(urban) - 4.78(\log_{10} f_c)^2 + 18.33\log_{10} f_c - 40.94$

(2) Hata Model

- It is accurate for $d > 1$ km (good for large cells in 1G, 2G, 3G)
- But, it is not good for micro-cell with radius < 1km, or for cellular systems using frequencies > 1.5GHz (like 3G, 4G, and some 2G systems).

(3) COST-Hata Model

- European committee named COST-231 (cooperative for scientific & technical research), developed an extension to Hata model for higher freq up to 2 GHz.
- Model is known as COST-Hata model and is widely used and it is given by:

$$PL_{50}(urban)[dB] = 46.3 + 33.9\log_{10} f_c - 13.82\log_{10} h_{te} - a(h_{re}) + (44.9 - 6.55\log_{10} h_{te})\log_{10} d + C_M$$

  - $C_M = 3$ dB for large urban centers (0 dB for small city/suburban areas)
  - f_c is now in the range 1500MHz - 2000MHz.
  - Other parameters remain the same as in the original Hata model.

However, the problem of inaccurate indoor and micro-cell (d<1km) propagation models remains.

(4) The Stanford University Interim (SUI) model

- It is developed for IEEE 802.16 (WiMAX) system.
- It can be used for base station antenna height h_{tx} from 10m to 80m, the receiving antenna height h_{rx} between 2m and 10m and the cell radius between 0.1km and 8km.
- It can be used for path loss predictions in rural, suburban, and urban areas via the three different terrain types: Hilly, flat , dense vegetations.
- Since 3G & 4G typically operate in 2/2.5, 3/3.5, upto 6GHz range, using the SUI model for link budget in these networks give accurate result.
- Other 4G: 3GPP Models for LTE system [see Ref. 8]

Terrain	Path Loss	Area	Vegetation	Model Parameters		
				a	b	c
Type A	Highest	Hilly	Very Dense	4.6	0.0075	12.6
Type B	Moderate	Flat	Very Dense	4	0.0065	17.1
Type C	Moderate	Hilly	Rare	4	0.0065	17.1
Type D	Lowest	Flat	Rare	3.6	0.005	20

Note: since basic Wimax assumed Backhaul service, vegetations & hills are emphasized.

(4) SUI Model

- Expression for calculating the path loss according to SUI Model is given by:

$$PL_{SUI}[dB] \;=\; A + 10n\log_{10}(\frac{d}{d_0}) + X_f + X_h + S, \qquad ford \;>\; d_0$$

where $A = 20\log_{10}\frac{4\pi d_0}{\lambda}$ and λ in meters.
$n = a - bh_{tx} + \frac{c}{h_{tx}}$, where a, b, and c depend on terrain types (see Table 1).
d: is the distance (in meters) between BS and receiving antenna of the MS,
d_0: is set to 100m.
$X_f = 6\log_{10}\frac{f}{2000}$ is the correction parameter for frequencies above 2GHz.
Correction parameter for the receiver antenna height is given by:

$$X_h = \begin{cases} -10.8\log_{10}\frac{h_r}{2} & \text{for terrain A, B} \\ -20\log_{10}\frac{h_r}{2} & \text{for terrain C} \end{cases}$$

S is a lognormal distributed factor that is used to account for shadowing owing to trees and other clutters and has a value between 8.2 dB : 10.6 dB.

- It estimate the path loss in the frequency range 1900MHz to 11GHz.

Indoor Propagation Models: To characterize radio propagation inside building

- Indoor channels may be classified as either LOS or obstructed (OBS), with varying degrees of clutters and it is affected by: (1) building layout (2) construction materials (3) Partition losses in same floor and in between
- Propagation models differs in two factors (1) distance covered is much small (2) variability of the environment is much greater.
- Several models have been proposed, but popular ones are:
  (1) Log-distance Path Loss Model (2) Indoor Attenuation Factor Model

(2) Log-distance Path Loss Model

- It has been shown by many researchers to obey the distance power law:

$$PL(d)[dB] = PL(d_0)[dB] + 10n\log_{10}(\frac{d}{d_0}) + X_\sigma$$

where n depends on the surroundings/building type, and X_σ is a normal random variable (in dB) with standard deviation σ. n ranges from 1.6-3.3 and σ ranges from 3-14dB.

(2) Log-distance Path Loss Model

Building	Frequency (MHz)	n	σ (dB)
Retail Stores	914	2.2	8.7
Grocery Store	914	1.8	5.2
Office, hard partition	1500	3.0	7.0
Office, soft partition	900	2.4	9.6
Office, soft partition	1900	2.6	14.1
Factory LOS			
Textile / Chemical	1300	2.0	3.0
Textile / Chemical	4000	2.1	7.0
Paper / Cereals	1300	1.8	6.0
Metalworking	1300	1.6	5.8
Suburban Home			
Indoor Street	900	3.0	7.0
Factory Obstructed			
Textile / Chemical	4000	2.1	9.7
Metalworking	1300	3.3	6.8

Path loss exponent, and standard deviation measured in different building types for indoor propagations

Indoor Propagation Models

(2) Indoor Attenuation Factor Model

- In-building, site-specific, propagation effects can be obtained by adding experimental data for floor and partition losses to an analytical or empirical path-loss model, $PL(d)$, above, to accurately estimate the received signal strength for indoor users:

$$PL_{indoor}[dB] = PL_{outdoor}[dB] + \sum_{i=1}^{N_f} FAF + \sum_{i=1}^{N_P} PAF_i$$

- FAF and PAF denotes respectively the floor attenuation factor for the i^{th} floor, and the partition attenuation factor for the i^{th} partition traversed by the signal.
- N_f and N_p are the numbers of floors and partitions traversed by the signals.
- Generally speaking, attenuation per floor is greater at the first floor, than the incremental attenuation caused by each additional floor.
- After five or six floor, only little extra FAF will be experienced.

(2) Indoor Attenuation Factor Model

Building	FAF(dB)	σ (dB)	# Loc.
Office Building 1:			
Via One Floor	12.9	7.0	52
Via Two Floors	18.7	2.8	9
Via Three Floors	24.4	1.7	9
Via Four Floors	27.0	1.5	9
Office Building 2:			
Via One Floor	16.2	2.9	21
Via Two Floors	27.5	5.4	21
Via Three Floors	31.6	7.2	21

Typical FAF Measurements

Partition type	Partition Losses
Cloth partition	1.4
Double plasterboard wall	3.4
Foil insulation	3.9
Concrete wall	13
Aluminum siding	20.4
All metal	26

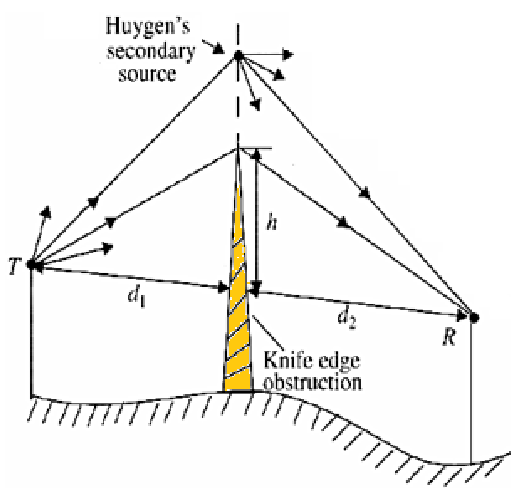
Typical Partition Losses for Different Materials

Homework

Homework 4

1. Using the SUI model and the WiMAX BS & MS parameters to predict received signal strength at a distance $d = 1.3$ km in a WiMAX cell, when the transmitter and receiver have a clear, unobstructed line-of-sight (LOS) path between them (use terrain type C). Using the minimum usable power for WiMAX receiver, predict the maximum coverage of WiMAX BS in LOS scenario. [Hint: check WiMAX website for standard values for BS & MS transmitted power, antenna heights etc., needed in the SUI model, also assume $f = 3$ GHz].
2. Repeat above for the case when there is a non-LOS (multipath) transmission between the transmitter and the receiver (Use terrain type A).
3. How do these numbers compare with the 3G cellular (GSM)?

Knife-Edge Diffraction Geometry



The field strength at point R is a vector sum of the fields due to all of the secondary Huygen's sources in the plane above the knife edge

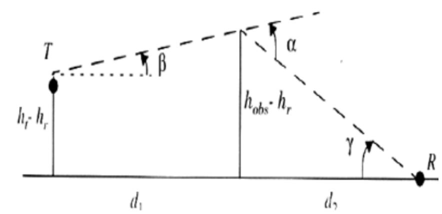
Knife-Edge Diffraction Geometry

1. Predicting strength of radio signal in the shadow of an obstacle is a vital job for propagation engineers.
2. Diffraction allows radio signals to propagate around the curved surface or propagate behind obstructions
3. Based on Huygen's principle of wave propagation: *"all points on a wavefront can be considered as point sources for the production of secondary wavelets that combine to produce a new wavefront in the direction of propagation"*

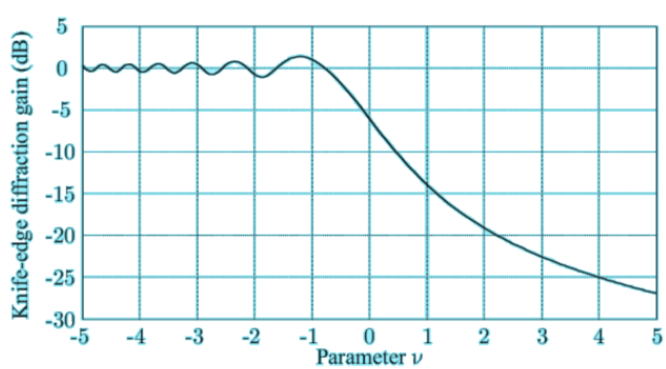
Knife-Edge Diffraction Model

Knife-Edge Diffraction Model

1. Knife-Edge Diffraction Model: is a theoretical mathematical model to predict the signal strength in shadow of an obstacle relative to that without obstacle.
2. Diffraction Loss L_d: the ratio of signal strengths with and without the obstacle.
3. This loss is affected by path geometry and frequency of operation.
4. All of the relevant factors can be summarized into a single parameter called Diffraction parameter or Fresnel parameter: $\nu = h\sqrt{\frac{2(d_1+d_2)}{\lambda d_1 d_2}} = \alpha\sqrt{\frac{2d_1 d_2}{\lambda(d_1+d_2)}}$ where d_1 and d_2 distance along LOS path, h: screening hight.



$$\alpha = \gamma + \beta = \frac{h(d_1+d_2)}{d_1 d_2}$$



Knife-Edge Diffraction

1. If $h = 0$ and hence $\nu = 0$ the diffraction loss equals ($\approx$ 6dB)
2. knife-edge diffraction gain is often referred as relative signal strength which means that signal strength will fall by 6 dB as RX approaches the shadow boundary but before it enters into the shadow region.
3. The Fresnel parameter must be $\nu \approx -0.8$, that is, h is negative to reduce the diffraction loss to zero and only then the presence of the edge can be ignored.

Knife-Edge Diffraction

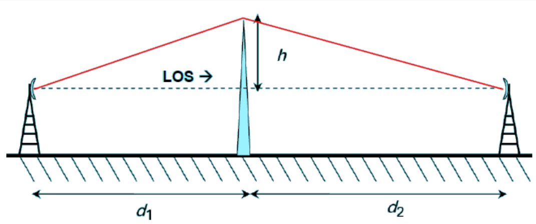
Knife-Edge Diffraction

1. For values of ν (-0.7 up to 1.5) the following approximation is valid: $L_d = 6.9 + 20\log_{10}(\sqrt{(\nu - 0.1)^2 + 1} + \nu - 0.1)$ dB
2. As receiving point moves deep into the shadow and becomes very large, the equation for diffraction loss can be approximated to $L_d = 13 + 20\log\nu$ for $\nu > 1.5$.
3. Deep in the shadow of an obstacle, the diffraction loss increases with $20\log\nu$.
4. Note: ν is directly proportional to h & inversely prop. to square root of λ.
5. So, if you double the frequency, deep in the shadow of an obstacle, the loss will increase by 3 dB and so on.
6. So, radio waves of longer λ will penetrate more deeply into shadow of an obstacle.

Example

Example 2:

Considering the geometry of the shown Fig. (a) determine the diffraction loss caused for $d_1 = 10$ km, $d_2 = 5$ km and $h = 20$m. (b) Perform the calculation at frequencies of 1 GHz and 10 GHz to compare.



Solution

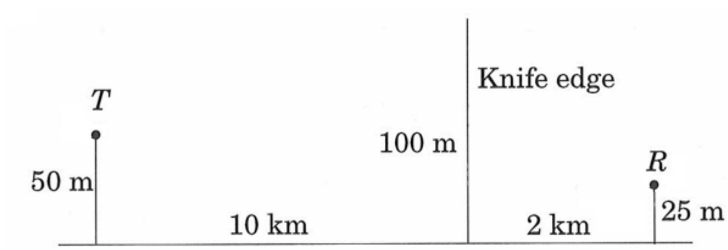
- (At 1 GHz): $\lambda = 0.3$ m, $\nu = 0.89$, $L_d = 13.2$
- (At 10 GHz): $\lambda = 0.03$ m, $\nu = 2.83$, $L_d = 21.9$

Therefore, as frequency increases the diffraction loss increases.

Example

Example 3:

Given the following geometry, determine (a) the loss due to knife-edge diffraction, and (b) the height of the obstacle required to induce 6 dB diffraction loss. Assume $f = 900MHz$

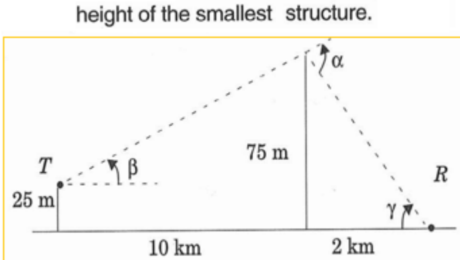


Example

Solution

(a) The wavelength $\lambda = \frac{c}{f} = \frac{3 \times 10^8}{900 \times 10^6} = \frac{1}{3}$ m.

Redraw the geometry by subtracting the height of the smallest structure.



$$\beta = \tan^{-1}\left(\frac{75-25}{10000}\right) = 0.2865^\circ$$

$$\gamma = \tan^{-1}\left(\frac{75}{2000}\right) = 2.15^\circ$$

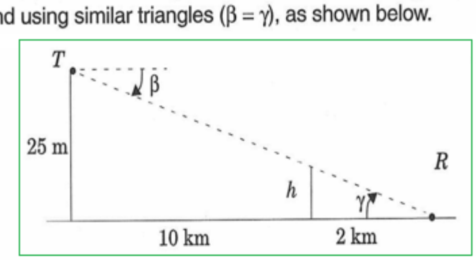
and $\alpha = \beta + \gamma = 2.434^\circ = 0.0424$ rad

Then using Equation (4.56)

$$\nu = 0.0424\sqrt{\frac{2 \times 10000 \times 2000}{(1/3) \times (10000 + 2000)}} = 4.24.$$

From Figure 4.14 or (4.61.e), the diffraction loss is 25.5 dB.

(b) For 6 dB diffraction loss, $\nu = 0$. The obstruction height h may be found using similar triangles ($\beta = \gamma$), as shown below.



It follows that $\frac{h}{2000} = \frac{25}{12000}$, thus $h = 4.16$ m.

Models for Multiple Diffracting Edges

- A second or more knife edges are placed around the original knife edge as shown in Fig. and the RX is in the shadow of all these secondary edges.
- This situation becomes much more complicated in terms of electromagnetic analysis of signal strength in the shadow, often referred to as Fresnel integral.
- Approximate models are commonly used, the most commonly used are: (1) Bullington (2) Deygout (3) pstein–Petersen; and none of them is perfect but can be used depending of each case.